Black Holes in Galactic Nuclei: the Promise and the Facts

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Abstract It has long been suspected that Active Galactic Nuclei are powered by accretion of matter onto massive black holes and this belief implies their presence in the nuclei of most nearby galaxies as "relics" of past activity. Just a few years ago this was considered a paradigm but, recently, new ground-based and Hubble Space Telescope observations are producing a breakthrough in our knowledge on massive black holes. I will review the evidence for the existence of black holes in galactic nuclei and how their presence is related to host galaxy properties and AGN activity.

0.1 A Brief Historical Introduction

In November 1783 John Michell presented to the Royal Society his idea of a *dark star*, a star so massive that the escape velocity from its surface is larger than the speed of light. Combining the corpuscolary theory of light with Newton's theory of gravitation, he found that a star with the same density as the Sun but escape velocity equal to c would have radius $R = 486\,\mathrm{R}_\odot$ and mass $M = 1.2 \times 10^8\,\mathrm{M}_\odot$. Michell also pointed out that, although dark stars are invisible, their presence could be inferred from the motion of other luminous bodies orbiting around them. Similar ideas were independently presented in 1796 by Laplace in his *"Exposition du système du monde"*.

In 1916 Karl Schwarzschild presented his exact solution of Einstein field equations deriving the well-known *Schwarzschild radius* which Michell had *exactly* determined although starting from *wrong* assumptions. The term *black hole*, which is now commonly used, was not coined until 1967 by John Wheeler and the first observational evidence for the existence of a black hole was given in the early 70s by the observations of the binary X-ray source Cygnus X-1. The discovery of quasars with their enormous energy output from small volumes of space suggested that they were powered by accretion of matter onto very massive black holes residing in galactic nuclei [29]. The first observational evidence was found in the galaxy M87 whose nucleus seemed to host a $5{\times}10^9\,\mathrm{M}_\odot$ black hole [44]. The supermassive black holes (hereafter BHs) hosted in galactic nuclei, with masses in the range $10^6 - 10^{10}\,\mathrm{M}_\odot$, are the topic of this review. Observational evidences for the existence of BHs in galactic nuclei up to the early '90s are summarized in a review

by Kormendy & Richstone [17]. At that time only a handful of BHs were known from ground-based and early HST observations.

0.2 Observational Evidences

There are several reasons why BHs should be present in the nuclei of active galaxies (e.g. [17]) but why should BHs be present in normal galaxies? AGNs are powered by mass accretion onto a BH and were more numerous and powerful in the past ($z \simeq 2-3$). Thus one expects that a significant fraction of local luminous galaxies should host black holes of mass $10^6 - 10^{10}\,\mathrm{M}_\odot$, relics of past activity (see § 0.4). For example, a quasar emitting $L = 10^{12}\,\mathrm{L}_\odot$ is powered by an accretion rate $\dot{M} = L/\epsilon\, c^2 \simeq 0.7\,\mathrm{M}_\odot/\,\mathrm{yr}$ (with efficiency $\epsilon = 0.1$) onto a BH. If the activity lasts for 10^8 yr, it will increase the BH mass by $\sim 7 \times 10^7\,\mathrm{M}_\odot$.

The existence of a BH can be inferred by the gravitational effects on the surrounding gas or stars, as foreseen by Michell. In principle, one measures the velocity field of gas and/or stars in the circumnuclear region of a galaxy and derives the gravitational potential ϕ required to sustain the observed motions. If the gravitational potential due to the luminous mass cannot account for ϕ then an additional component ϕ_{BH} is required to explain the observed motions. If it is spatially "unresolved" at the observational limit it is called a *Massive Dark Object* (MDO) and is a BH candidate. One can then easily determine M_{BH} ($\phi_{\mathrm{BH}}(r) = -GM_{\mathrm{BH}}/r$).

The two most relevant cases. The closest galactic nucleus hosting a BH is our galactic center and this currently represents the best case for a BH. With ground-based high-spatial-resolution observations (e.g. speckle interferometry, adaptive optics) it has been possible to measure stellar positions with high accuracies ($\pm 1-5$mas) thus detecting their proper motions. Combining these proper motions with spectroscopic measurements, the velocity vector $\vec{v}$ of many stars around SgrA* (the radio source identified with the center of our galaxy) has been directly measured; typical velocities are of the order of a few $100\,\mathrm{km\,s^{-1}}$ with accuracies of $\pm 20 - 30\,\mathrm{km\,s^{-1}}$ [18, 21, 9]. Ghez et al. [21], using adaptive optics at Keck, have been able to trace curved stellar orbits, a clear indication of acceleration. Within the errors, acceleration vectors all intersect at the location of SgrA*. All the available data on SgrA* have been analyzed in detail by Genzel et al. [18] and the main results can be summarized as follows: star motions can be explained only with a compact ($\rho_{\mathrm{BH}} \geq 10^{12.6}\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$) dark ($M/L > 100\,\mathrm{M}_\odot/\,\mathrm{L}_\odot$) mass concentration. Since any dark cluster would have a lifetime less than $\sim 10^8$yr (see also [35]), too short with respect to the Hubble time, the data show the presence of a BH with mass $M_{\mathrm{BH}} = 2.6 - 3.3 \times 10^6\,\mathrm{M}_\odot$. An anisotropy independent estimate of the distance of the Galactic center is $D = 7.8 - 8.2\,\mathrm{kpc}$ fully consistent with previous estimates based on independent methods. A recent review by Melia & Falcke presents the latest observational results and physical interpretation [37].

The second best case for a BH is in the nucleus of the nearby spiral galaxy NGC 4258, where high spatial resolution VLBA spectroscopic observations of the H_2O maser emission have shown the presence of high velocity maser spots. Their velocity field and location in the plane of the sky indicate that they are part of a thin, warped disk circularly rotating around the galactic nucleus with Keplerian velocities. The velocity field suggests that there is a dark mass concentration of $3.9{\times}10^7\,\mathrm{M}_\odot$ within 0.14 pc, yielding a mass density of $\rho_{\mathrm{BH}} > 4 \times 10^9\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$ [39]. Such an object can only be a

black hole because all star clusters with that density would undergo collapse within a few 10^8 yr [35]. The detection of the maser proper motions, with indications of acceleration, has allowed a distance estimate accurate to $\simeq 4\%$, similarly to the Galactic center case. The review by Moran, Greenhill & Herrnstein [40] presents more details and a summary of BH detections with water masers.

The Galactic center and NGC 4258 are really "textbook" cases. Nowadays, proper motions can be measured only in our Galactic Center, and galaxies with "well behaving" maser disks are extremely rare. Out of ~ 700 galaxies observed, 22 H_2O masers have been detected and only 6 have a "disk" structure which allows a determination of the BH mass. NGC 4258 is still the most convincing case [40].

Results from the Hubble Space Telescope. In general, what one can measure is not the velocity vector $\vec{v}$ of a single star or gas cloud but the overall distribution $f(v)$ of the velocity components along the line of sight. Furthermore, $f(v)$ is a volume average over a column elongated along the line of sight with the base set by the spatial resolution of the observations. Thus one must deal with 2-dimensional information of a 3-dimensional structure: detecting a BH and measuring its mass is not as "simple" and "straightforward" as for the Galactic Center and NGC 4258. I will not discuss here the detailed methods to measure BH masses with stellar dynamics or gas kinematics. The reader can refer to [48, 34, 4] for a detailed description of BH mass measurements with stellar dynamics and to [30, 32, 3] for gas kinematics. In any case, to detect BHs one needs spectral information at the highest possible angular resolution in order to spatially resolve the BH sphere of influence [2] where the BH dominates over the galactic potential. The radius $r_{\rm BH}$ of the BH sphere of influence is

$$r_{\rm BH} = \frac{GM_{\rm BH}}{\sigma_*^2} \simeq 4.3 \left(\frac{M_{\rm BH}}{10^7\,{\rm M}_\odot}\right) \left(\frac{100\,{\rm km\,s^{-1}}}{\sigma_\star}\right)^2 {\rm pc} \qquad (1)$$

where σ_* is the velocity dispersion of the stars in the nuclear region. This can be translated to an angular size in the plane of the sky,

$$\theta_{\rm BH} \simeq 0.1 \left(\frac{M_{\rm BH}}{10^7\,{\rm M}_\odot}\right) \left(\frac{100\,{\rm km\,s^{-1}}}{\sigma_\star}\right)^2 \left(\frac{10\,{\rm Mpc}}{D}\right) arcsec \qquad (2)$$

where D is the galaxy distance. The small values of $\theta_{\rm BH}$ obtained for typical $M_{\rm BH}$, σ_* and D values explains why, up to the early 90s, there have been few BH detections from the ground. The recent breakthrough due to HST is a result of its high spatial resolution which is almost an order of magnitude better than from the ground.

I will now briefly outline a few significant cases for BHs from HST observations. The first one is that of M87, the giant elliptical galaxy in Virgo with a radio/optical jet. Sargent et al. [44] made the first claim for the presence of a BH with $\sim 5 \times 10^9\,{\rm M}_\odot$ and [23] measured high velocities with HST/FOS in the nuclear gas disk thus strengthening the case for a BH. The case for the presence of a BH has been settled with FOC longslit spectra, the first ones obtained from HST: careful modeling taking into account instrumental effects gave $M_{\rm BH} = (3.2 \pm 0.9) \times 10^9\,{\rm M}_\odot$ [30]. The first STIS detection of a BH is that in M84 where gas kinematics gave $M_{\rm BH} = (1.5 \pm 0.9) \times 10^9\,{\rm M}_\odot$ [5]. Using stellar dynamics, van der Marel et al. [49] combined HST/FOS and ground based data of the nuclear region of M32. They detected a dark mass concentration $M_{\rm BH} = (3.4 \pm 1.6) \times 10^6\,{\rm M}_\odot$ confined within a region of 0.3pc across. This was the first detection

of a BH in a quiescent galaxy. Since then there have been many BH detections with HST/STIS stellar dynamical or gas kinematical studies and the most notable ones are certainly that of NGC 1023 [4] and NGC 3245 [3], respectively.

The most secure BH detections up to March 2001 are summarized by Kormendy & Gebhardt [16]. It is immediately clear from their table that most of the BH detections are in E-S0 galaxies (29 out of 36). In order to fill this gap we (Axon, Marconi et al.) are just completing an HST/STIS survey of a sample of 54 Sb, SBb, Sc and SBc galaxies [33]. Preliminary results from this survey include the case of NGC 4041 (Marconi et al. 2002, in prep), where we have set a limit of $< 10^6\,\mathrm{M}_\odot$ to the mass of the BH, significantly lower than expected from the $M_{\rm BH}$-$L_{\rm Bulge}$ correlation (see § 0.3) and that of NGC 4258 (Axon et al. 2002, in prep). In the latter case the BH mass estimate from HST/STIS spectroscopy agrees with the H_2O maser estimate thus confirming the validity of gas kinematical measurements.

Ground Based Observations. HST has two fundamental limitations: its size, 2.5m, and its lack of a near-IR longslit spectroscopic facility and both factors do not allow observations of faint or obscured objects. Eight-meter-class ground-based telescopes with good seeing and adaptive-optics can overcome these limitations. An example is given by the detection of a BH in Centaurus A, a famous radio galaxy whose nucleus is obscured by at least $A_V \sim 7$mag. VLT/ISAAC Paβ (1.28μm) spectroscopy, with 0.″5 seeing, of the nuclear gas disk has shown the presence of a BH with $M_{\rm BH} \sim 2\times10^8\,\mathrm{M}_\odot$ [32]. Similarly, Keck Paα spectroscopy have revealed a BH in Cygnus A with $M_{\rm BH} \sim 3\times10^9\,\mathrm{M}_\odot$ (Tadhunter et al. 2002, in prep).

Going Farther? The high spatial resolution required limits BH searches to nearby ($D < 100$ Mpc) objects. How is it possible to go farther? A possibility is offered by reverberation mapping of broad emission lines in Seyfert 1 galaxies and quasars. The time lag, $\tau_{\rm BLR}$, between the continuum light curve and that of a broad line (e.g. Hα) is interpreted as light travel time between the compact continuum source and the more extended *Broad Line Region* (BLR): thus $R_{\rm BLR} = c\tau_{\rm BLR}$ is an average BLR radius. Assuming virialized motions of the BLR clouds, one can combine $R_{\rm BLR}$ with the Full Width at Half Maximum (FWHM) of the line and obtain $M_{\rm BH} \simeq 1.45 \times 10^5\,\mathrm{M}_\odot (c\tau_{\rm BLR}/1\,\mathrm{lt\,day})(FWHM/1000\,\mathrm{km\,s^{-1}})^2$ [25, 50, 26]. The virial assumption has been directly tested in the case of NGC 5548 but many systematic uncertainties are present in this kind of estimate (see [27] and references therein). However, a strong support for the reliability of this method comes from the agreement of BH estimates from reverberation mapping with the $M_{\rm BH} - \sigma$ correlation (§ 0.3).

Another more indirect method uses the FWHM of the broad line (Hβ) combined with the continuum luminosity. The size of the BLR, estimated from the correlation between $R_{\rm BLR}$ and the monochromatic luminosity L_λ at 5100Å [26], is combined with the FWHM of the Hβ line to derive the BH mass. In [28, 36] and references therein the reader can find applications of this method which seems to provide reliable BH mass estimates. Note however that the $R_{\rm BLR}$-L_λ(5100Å) correlation is not tight at all (see Fig. 6 in [26])!

Are they really Black Holes? What I have called BHs are really massive dark objects. The possibility that an MDO is not a cluster of dark objects (e.g. stellar mass black holes, neutron stars etc.) can be safely ruled out for the Galactic Center, NGC 4258 [35] and probably M32 [49] on the basis of the short lifetimes of such clusters. In the two former cases observations have probed down to $\sim 4\times10^4$ Schwarzschild radii, still far from the General Relativity regime. The definitive proof that these MDOs are really BHs would

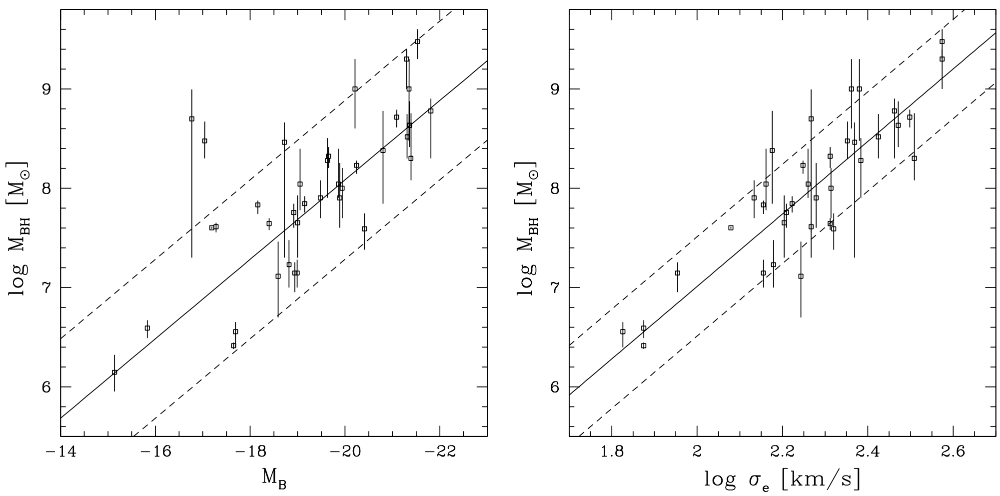

Figure 1: (a) $M_{\rm BH}$-$L_{\rm Bulge}$ correlation. M_B is the absolute magnitude of the bulge in the B band. The dashed lines represent a ± 0.8 range in BH mass around the best fit relation. (b) $M_{\rm BH}$-σ correlation. The dashed lines represent a ± 0.5 range in BH mass around the best fit relation. Data from [16].

be the detection of relativistic motions close to the event horizon. This seems to have happened in the case of the galaxy MCG-6-30-15, where the broad red wing of the Kα Fe line at $\sim$ 6keV has been interpreted as due to relativistic effects close to the event horizon [47]. New XMM observations [51] have confirmed these results and presented evidences for a rotating black hole and magnetic extraction of BH spin energy as in the Blandford-Znajek mechanism. Though model dependent, these are very exciting news and, indeed, the line profile of the Kα Fe line is a unique probe of the region close to the event horizon, in principle allowing one to distinguish between a Schwarzschild or a Kerr BH [10].

0.3 Black Holes and Host Galaxy Properties

The many reliable BH detections ($\sim$ 40) allow demographical studies. [17] reported a correlation between BH mass and bulge luminosity which was confirmed by following studies [34, 25]. More recently a tighter correlation has been found between the BH mass and the central stellar velocity dispersion of the host spheroid [13, 19]. The slope of the $M_{\rm BH}-\sigma$ correlation is still a matter of debate and is in the range $M_{\rm BH} \sim \sigma^{4-5}$. The two correlations are displayed and compared in Fig. 1. The $M_{\rm BH}-\sigma$ correlation does appear tighter but this could be a consequence of uncertainties in bulge luminosity estimates. Indeed, [36] estimate the BH mass in a sample of AGNs using the width of the Hβ line and re-analyze the $M_{\rm BH}$-$L_{\rm Bulge}$ relation finding that its scatter is similar to that of the $M_{\rm BH}$-σ relation ($\sim$ 0.3dex). This comes from better estimates of the bulge luminosities obtained from full 2D bulge-disk decomposition and from the use of the R band which is less contaminated by extinction and star formation than the commonly used B band.

The BH mass also correlates with the light concentration of the bulge and the tightness of the correlation is comparable with that of the $M_{\rm BH}-\sigma$ relation [22].

These correlations have three important consequences. The first one is that the BH formation must be related to the formation of the host spheroid. The second one is that the $M_{\rm BH}$ values estimated using reverberation mapping and Hβ line widths are reliable since they agree well with the $M_{\rm BH}-\sigma$ relation. This also implies that BH masses of AGNs are on average indistinguishable from those of normal galaxies [20, 36]. Finally, the third consequence is that the correlations are "cheap" empirical estimators of the BH mass in large samples of objects. For example, [38] use the $M_{\rm BH}-\sigma$ relation to estimate the $M_{\rm BH}/M_{\rm Bulge}$ ratio in a sample of elliptical galaxies. They find that $\log(M_{\rm BH}/M_{\rm Bulge}) \sim -2.90$ with r.m.s. ~ 0.45. This implies that the local density in black holes is $\rho_{\rm BH} \sim 5\times10^5\,{\rm M_\odot\,Mpc^{-3}}$.

0.4 Black Holes and AGN Activity

To test if the BHs in the nuclei of nearby galaxies are relics of AGN activity one can estimate the integrated comoving energy density from AGNs

$$u = \int_0^\infty \int_0^\infty \Phi(L,z) L dL \frac{dt}{dz} dz = 1.06\times10^{-15}\,{\rm erg\,cm^{-3}} \tag{3}$$

Φ is the luminosity function of type 1 AGNs (e.g. quasars or, in general, AGNs with broad emission lines in their optical spectra) used by [31]. With an accretion efficiency ϵ the relic mass density is $\rho_{\rm BH} = u/(\epsilon c^2) = 1.74\times10^5(\epsilon/0.1)^{-1}\,{\rm M_\odot\,Mpc^{-3}}$. This number must be multiplied by the ratio between type 2 (i.e. those without broad emission lines) and type 1 AGNs, R_{21}, to account for the whole AGN population. Hence $\rho_{\rm BH} \sim 7\times10^5\,{\rm M_\odot\,Mpc^{-3}}$ with $R_{21} = 4$, the canonical number used in AGN unified models. This is in agreement with $\rho_{\rm BH} = (5\pm2)\times10^5\,{\rm M_\odot\,Mpc^{-3}}$, the BH mass density estimated by combining the $M_{\rm BH}-L_{\rm Bulge}$ correlation with bulge luminosity functions [31]. This argument has been presented in many papers following from the work by Soltan [46] and Chokshi & Turner [7]. The density in relic BHs can also be estimated from the X-ray background emission: assuming that the XRB bump in the 10-30 keV spectral range constitutes the integrated emission from *all* AGNs, one derives the AGN energy density and then $\rho_{\rm BH} \simeq 3-6\times10^5\,{\rm M_\odot\,Mpc^{-3}}$ [12, 43]. All the above values are in good agreement. In particular, the expected density in AGN relics matches the BH mass density derived from local bulges indicating that most of the BH masses are relics of past AGN activity. It is possible to reproduce the above arguments in a more refined way dealing directly with the BH mass function and not only with integrated values ($\rho_{\rm BH}$). [31] compare the BH mass function (MF) expected from AGN activity with the BH MF derived from local bulges [43]. The main conclusions are that, using standard assumptions on AGN activity, compatible with current knowledge, one can reproduce the BH MF of local bulges *both* in shape and normalization (Fig. 2).

There have been suggestions of a correlation between radio emission and the mass of the BH. In particular it seems the radio-loud quasars are characterized by the most massive BHs ([14, 36] and references therein). However, Ho [24] finds that the radio continuum power, either from the whole galaxy or from the nuclear core alone, correlates poorly with $M_{\rm BH}$. The degree of radio loudness (radio-to-optical luminosity) is strongly

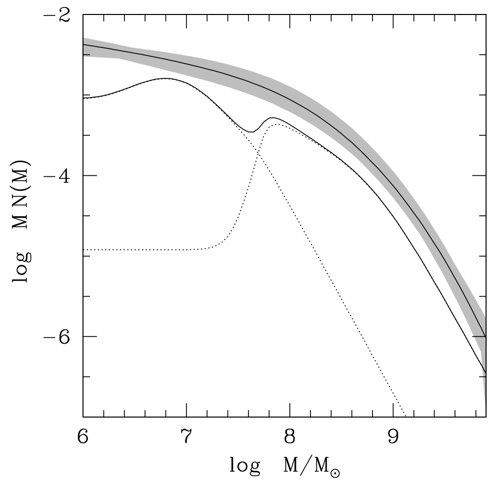

Figure 2: Local BH mass function $N(M)$ ($\#/\mathrm{d}M/\mathrm{Mpc}^3$) from bulges (solid line in gray area) compared with that expected from the activity of type 1 AGNs. The dotted lines represent the contributions from low and high luminosity objects. The mass function of AGN relics should then be multiplied by $\sim 2-4$, the ratio of type 2 to type 1 objects, to account for the whole AGN population. Adapted from [31].

inversely correlated with $L/L_{\rm Edd}$, which is taken as evidence for advection-dominated accretion. The issue of the correlation $M_{\rm BH}$-Radio Power is still much debated and potentially very important because it could lead to the much sought unification between radio-loud and radio-quiet AGNs.

0.5 Black Holes and Galaxy formation

The physical reasons behind the correlations between $M_{\rm BH}$, bulge mass and σ are currently being investigated by several authors and only a few examples will be presented here. [45, 11] propose a scenario in which BH growth is self regulated: the BH forms in the galaxy nucleus before all the bulge gas is turned into stars. Then it accretes gas giving rise to quasar-like activity. When the BH mass is large enough the radiation pressure and wind produced by AGN activity will sweep away the gas, blocking growth and star formation in the spheroid. [45] use an energy argument to determine this critical mass of the BH and find $M_{\rm BH} \propto \sigma^5$. However [11] uses a different argument based on force balance, finding $M_{\rm BH} \propto \sigma^4$. [1] model the bulge as a rotating isothermal sphere and the BH growth is stopped when the centrifugal radius of the collapse flow exceeds the capture radius of the BH, implying $M_{\rm BH} \propto \sigma^4$. Similarly [6] show that if the BH growth is completely self regulated by the luminosity output, $M_{\rm BH} \propto \sigma^5$ is to hold at all σ's. On the other hand, if the feedback is not important $M_{\rm BH} \propto \sigma^4$ will hold at high σ while at lower values it will soften to $M_{\rm BH} \propto \sigma^3$, when the growth is completely supply-limited.

An accurate determination of the slope of the $M_{\rm BH} - \sigma$ correlation is thus important to distinguish between self-regulated BH growth ($M_{\rm BH} \propto \sigma^5$) or growth determined by ambient conditions ($M_{\rm BH} \propto \sigma^4$). In the former case, the bulge mass in stars is set by $M_{\rm BH}$.

[15] show that the observed correlations $M_{\rm BH}$-$L_{\rm Bulge}$ and $M_{\rm BH}$-σ can be reproduced both in slope and scatter with their model in which bulges and supermassive black holes both form during major mergers. Observational support to the idea of BH from merging comes from [42]. They study the central cusp slopes and core parameters of early type galaxies using a sample of objects observed with HST and find that the observational

trends are reproduced in the framework of binary black hole mergers but not in that of adiabatic growth models. [8] combine the $M_{\rm BH}$-σ relation with other scaling relations for elliptical galaxies such as the Faber-Jackson relation and the fundamental plane relation. In order not to produce effective radii of elliptical galaxies larger than observed, the rule for adding the mass of merging BHs must be substantially different from what is assumed, or the merging process must involve a significant dissipative phase.

0.6 Conclusions

The observational evidences presented so far suggest the ubiquity of BHs in the nuclei of all bright galaxies, regardless of their activity. BH masses correlate with masses and luminosities of the host spheroids and, more tightly, with stellar velocity dispersions. These correlations constrain BH formation and growth but can also be used as empirical estimators of BH masses in large samples of objects.

Accretion of matter onto a BH during AGN phases can reproduce the mass function and account for the local density of BHs thus implying a strict relationship between BH growth and AGN activity.

However several issues remain to be solved since the field "Massive Black Holes in Galactic Nuclei" is still young. Following are some issues, both general and particular, which should be tackled in the near future.

– We have to prove unambiguously that the massive dark objects present in galactic nuclei are BHs by detecting relativistic motions close to their event horizon.

– Is the $M_{\rm BH} - \sigma$ correlation really tighter than the $M_{\rm BH} - L_{\rm Bulge}$ correlation or is it a consequence of inaccurate determinations of $L_{\rm Bulge}$?

– What is the slope of the $M_{\rm BH} - \sigma$ correlation? Solving this issue will indicate if BH growth is self-regulated or not.

– Up to what redshift can the correlations be used to estimate BH masses? Or alternatively, are the $M_{\rm BH} - L_{\rm Bulge}$ and $M_{\rm BH} - \sigma$ correlations valid throughout the evolution of a galaxy or just during its final stages?

– Some observational evidences and theoretical models suggest that a massive black hole could form from the merging of smaller BHs. What is the importance of merging in the growth of a BH related to mass accretion during AGN phases?

Apart from HST, which will continue detecting BHs in nearby galactic nuclei, further developments can be expected from the use of adaptive optics with 8m-class telescopes like VLT and Keck and, of course, from the launch of NGST. The use of interferometric techniques in BH searches must still be assessed but could produce a real breakthrough in spatial resolution allowing one to probe down to the milli-arcsecond level.

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